CHAPTER 5

CONTAMINATION OF THE COHANSEY AQUIFER BY PRICE'S PIT

INTRODUCTION

     Price's Pit occupies approximately twenty-two acres extending across the
boundary of Egg Harbor Township and the Town of Pleasantville, New Jersey
(see figure 8).   Until 1967, it functioned as a sand and gravel quarry.
During 1968, when the pit was excavated to within approximately two feet of
the water table, people from the surrounding area began to dump trash into it
with the permission of the owner, Charles Price.

     In 1970, Price applied to the New Jersey Department of Environmental
Protection (NJDEP) for a license to conduct a sanitary landfill operation.
The application listed the materials that Price intended to accept at the
landfill, and specifically excluded "Chemicals (Liquid or Solid)."   NJDEP
issued a certificate authorizing operation of a solid waste disposal
facility.

     The New Jersey State Sanitary Code requires that every landfill operator
submit a detailed sanitary design.   The NJDEP reviews each application and
the accompanying engineering plan to determine whether planned operations
pose a threat to health or the environment.   Price did not submit a plan to
the NJDEP until late 1971, and that submission did not mention the disposal
of chemicals.   At that time, he was already accepting and disposing of
chemical wastes.

     Only later, in 1972, did Price seek authorization to take delivery of
liquid and chemical wastes.   In its response, the NJDEP granted Price a
certificate subject to the conditions that:

          No liquid or soluble industrial wastes, petrochemicals,
          waste oils, sewage sludge, or septic tank wastes shall
          be received for disposal at this site.

          Observation well(s) shall be constructed for monitoring
          ground water conditions no later than six (6) months
          from the date of issuance of the Certificate of
          Registration.   Said observation well(s) shall be
          constructed according to standards established by the
          Department of Environmental Protection.

Despite those restrictions, Price continued to accept and dispose of
significant quantities of chemical and liquid wastes at the landfill until
the end of 1972.   Those wastes were disposed of carelessly. Wastes were

Figure 8. The Price's Pit Area

frequently poured into the landfill from an open spigot on a tank truck, and drums of chemicals were simply buried under piles of refuse.

In July 1972, the NJDEP inspected the landfill, cited Price for accepting chemical wastes, and formally advised him that he was in violation. Nonetheless Price continued accepting significant quantities of chemical wastes until November 1972. After that date, no chemical wastes were disposed of at the landfill, although it continued operating. In 1976, Price terminated landfill operations and covered the site with fill material. It has remained closed since then.

GEOHYDROLOGICAL CONDITIONS AND MIGRATION OF THE TOXIC WASTES FROM THE LANDFILL

Price's Pit is situated in a geographically sensitive area--an abandoned sand and gravel quarry. The site violates all of the common selection criteria for landfills accepting hazardous chemical wastes. It is located near water supply sources, it lies above sandy soils and above a water table less than 10 feet from the surface, and is above an aquifer flowing in the direction of public water supply wells.

During the period May 1971 to November 1972, Price accepted approximately 9 million gallons of the following toxic and flammable chemical and liquid wastes, either in drums or directly into the ground: acetone, acids (glycolic, nitric, and sulfuric), and spend acid wastes, acryloid, acryloid monomer and poly acryloid, caulking and spent caulking solvent, caustics and spent caustic wastes, cesspool waste, chemical resins and other waste chemicals, chloroform, cleaning solvents, ether and spent ether wastes, ethyl acetate, ethylene dichloride, fatty acids, glue wastes, grease and spent grease solvents, heptane, hexane, inks and waste ink residues, isopropanol, isopropyl alcohol, isopropyl ether, lacquer thinner, manganese dioxide, methanol, methyl ethyl ketone, methyl isobutyl ketone, methyl vinyl ketone, miscellaneous chemical laboratory wastes, mineral spirits, oil and waste oil products (No. 6 waste oil), paint, paint sludge, paint thinner and spent paint wastes, perfume wastes, phenols, phenolics, and phenolic solvents, resins, septic waste and sludge, (distillery) still bottoms, styrene and styrene wastes, tar, titanium wastes, toluene, xylene and xylol.

STUDIES OF THE PRICE SITE AFTER CLOSURE

After the Price site was closed, EPA officials and contractors took extensive water level measurements in the area. Those measurements showed that the hydraulic gradient in the area of the landfill slopes generally east and east-northeast from the landfill. The groundwater in the area, and contaminants in that groundwater, will therefore tend to flow east and east-northeast.

A leachate plume has been defined in the area of Price's Pit, although the precise contours of the plume have not been determined. A resistivity test that has been done is of limited utility because it cannot detect chlorinated hydrocarbons, which are often not conductive. Because certain of these chlorinated hydrocarbons, such as 1,2 dichloroethane (DCE), move more

rapidly than other contaminants, significant pollution can be present well in advance of the time it is detectable using resistivity. But the plume clearly emanates from Price's Pit and is the result of the chemical dumping that occurred there in 1971 and 1972: there are no other sources of pollution in the area that have significantly contributed to this plume of contaminants. The contaminants in the groundwater have followed, and are likely to continue to follow, the hydraulic gradient east and east-northeast from the landfill toward the Atlantic City Municipal Water Authority (ACMUA) wells. The speed of progress of the leachate from the landfill toward the ACMUA wells will probably range between .70 and .85 feet per day. Dissolved substances move with the groundwater as it flows along the hydraulic gradient, but not necessarily with the same velocity as the groundwater. Velocities will vary somewhat across the various contaminants.   Some pollutants, such as DCE, have a low retardation factor and move more rapidly in an aquifer than others.

Movement of the contaminants toward the ACMUA wells was confirmed by water samples taken from monitoring wells EPA 1A, located 1,300 feet east of the landfill, EPA 6, located 2,000 feet east of the landfill, and private well 38, located 2,400 feet east of the landfill (figure 8). Each of those wells show significant, though diluted, amounts of the contaminant DCE. Contaminants originating in the landfill should take between twelve and fifteen years from the date of disposal to reach the ACMUA wellfield. The closest ACMUA well is located 3,400 feet east of the landfill.

This rough order-of-magnitude calculation neglects the effect of the ACMUA wells on the movement of the contaminants. Pumping from large public water supply well field, such as Atlantic City's, significantly affects the hydraulic gradient in the area around the wells, increasing the velocity of groundwater (and pollutants contained in that water) moving toward those wells. Between the landfill and the ACMUA wells, there seems to be no geologic confining barrier in the upper 100 feet of the Cohansey Aquifer. Thus there is nothing to impede the flow of contaminants toward those ACMUA wells that draw water from wells lying less than 100 feet below the surface.

There is evidence of a clay confining bed under Price's Pit at a depth of approximately 130 feet. It seems that this clay layer extends continuously between the landfill and the ACMUA wells. If that layer is continuous and impermeable, wells drawing water from the Cohansey Aquifer below that layer will not be contaminated by leachate from the landfill. The limited testing done thus far reveals no contamination of groundwater lying between 150 and 200 feet below the surface.

EVIDENCE OF CONTAMINANTS IN DRINKING WATER

Between 1973 and the present, 12 observation wells were installed in or near Price's Pit. In addition, there are approximately 35 private wells in the vicinity of the landfill.

In December 1979, April, August, October, November, December 1980, and January 1981, employees of EPA and members of the Field Investigative Team (FIT)--employees of Fred C. Hart Associates, an engineering consulting

firm--collected water samples from specially drilled monitoring wells located in and near Price's Pit, and from existing public and private water wells in the vicinity of the landfill. Those samples were collected using standard and generally accepted protocols for groundwater sampling. They were then transported to the EPA Laboratory in Edison, New Jersey, or to one of the FIT contract laboratories, and then analyzed using EPA **procedures** for the 127 priority, and consent decree, pollutants.

Analysis of those samples revealed significant contamination of wells on the landfill and in the surrounding area. Testing of some of the monitoring wells and private wells detected the following contaminants, among others, in the groundwater. In terms of the Water Quality Criteria (WQC) promulgated by the EPA[2], some of those measured concentrations were as indicated in the following table. Many other contaminants were found at each of the above sites, including a variety of other metals, chlorinated hydrocarbons, and other chemical contaminants present in amounts greatly in excess of Water Quality Criteria concentrations.

TOXICOLOGICAL SIGNIFICANCE OF THE CONTAMINANTS

Many of the contaminants found in groundwater near, and in the vicinity of, the landfill are hazardous to the environment and to human health. For example:

(a) arsenic is a highly toxic metal and an established human carcinogen;

(b) cadmium is a highly toxic metal, a suspected carcinogen in man, and is known to be teratogenic in animals;

(c) lead is a toxic metal and suspected of being carcinogenic and teratogenic in humans;

(d) benzene is a highly toxic hydrocarbon and a potent carcinogen and teratogen;

(e) trichloromethane (chloroform) is highly toxic and a recognized carcinogen and teratogen;

(f) vinyl chloride is a toxic halogenated hydrocarbon, is carcinogenic and is a known mutagen;

(g) 1,2 dichloroethane is a toxic chlorinated hydrocarbon, is a known carcinogen and a suspected teratogen.

Inorganic compounds such as arsenic, cadmium, chromium, lead, nickel, zinc, and mercury have been widely used in industry since the 1930s. It has become conventional to refer to the concentrations associated with occupational exposures as "high" concentrations, and to the ambient environmental concentrations to which the general population is exposed as "low concentrations." And there is, for many of these contaminants, either the knowledge or the suspicion that they may be hazardous to human health even through exposures at "low" concentrations. Thus general-population

Table 13. Some Observed Priority-Pollutant Concentrations at Wells Near Price's Landfill

Well	Function and Location	Chemical	Representative Observed Concentration (Parts Per Billion)	Ratio to (Upper) Water Quality Standard Concentration
NJDEP Well 2	Monitoring well at eastern boundary of landfill	Arsenic	3.3×10^1	1.50×10^3
		Vinyl chloride	6.9×10^3	3.46×10^2
		1,2 dichloroethane	2.2×10^5	2.40×10^3
		Lead	7.0×10^2	1.40×10^1
EPA Well 6	Monitoring well 2,000 feet east of landfill	Chloroform	9.1×10^1	2.80×10^1
		Tetrachloroethylene	7.7×10^1	7.00
		1,2 dichloroethane	4.7×10^3	5.00×10^2
Dorsey Well (#41)	Private well 1,000 feet north-west of landfill	Arsenic	9.9	4.50×10^2
		Benzene	5.1×10^2	7.70×10^1
		Methylene chloride	1.3×10^2	6.80×10^1
Opie White Well (#15)	Private well 1,400 feet north-west of landfill	Arsenic	9.9	4.50×10^2
		Benzene	4.5×10^2	6.80×10^1
		Methylene chloride	1.1×10^2	5.80×10^1

health effects have come to be the focus of many of our environmental-health policy debates.

For these reasons, it is probably worth noting that many of the contaminants observed in wells in the Price's Landfill area are, by any reasonable standard, "high" concentrations. Some are higher than observed occupational exposures, and many are substantially higher than observed concentrations in polluted surface waters. In addition to being toxic, some of these compounds are carcinogenic and possibly mutagenic. The metals, in particular, are not degraded by natural processes and tend to persist in the environment.

Certain organic compounds, such as toulene, benzene, phenol, chloroform, methylene chloride, vinyl chloride, and dichloroethane have been commonly used industrial chemicals since the 1950s. The chlorinated hydrocarbons are poorly degraded by natural processes and thus tend to persist in the environment. For some, organ-specific toxicities have been established: the latter include toxicity to the liver (hepatotoxicity), the kidneys (nephrotoxicity), and the nervous system (neurotoxicity). And for others, effect-specific toxicities have been established or are suspected: the latter include cancer induction (carcinogenicity), birth defect induction (teratogenicity), and genetic effects (mutagenicity). All of the compounds listed above ((a) - (g)) have been designated as hazardous wastes and hazardous waste constituents under published EPA regulations, and are contaminants within the meaning of the Safe Water Drinking Act. Many of the other chemical wastes emanating from the landfill are known to be toxic and are known or suspected carcinogens and teratogens.

THE LIKELY EFFECT OF THE CONTAMINATION ON WATER SUPPLIES

Approximately thirty-five privately-owned homes are located on the northeast border of the landfill. Those homes have been using private wells for their water supply, drawing water from the Upper Cohansey Aquifer, with wells screened less than 100 feet below the surface. Many private wells in this area are contaminated by the leachate from the landfill. Private wells to the east and northeast of the landfill are likely to encounter strongly contaminated water if screened at depths of fifty to seventy feet below the surface, and somewhat less polluted water if screened at higher or lower depths.

The Atlantic City public water supply system includes fifteen wells and a reservoir. The reservoir is situated on a stream independent of the aquifer system in which the supply wells are screened. Ten operating wells draw water from the Cohansey Aquifer; two other wells draw water from the lower Kirkwood strata, and are screened at a depth of about 675 feet. The geohydrological data place the dispersed front of the plume about 2,500 feet east of the landfill, concentrated at about 40 to 70 feet below the water table. The plume is moving in the direction of four ACMUA wells which draw water from depths of approximately 60 to 100 feet.

Those four wells produced about forty-one percent of Atlantic City's daily water consumption during 1979 and 1980. All are located in the

direction in which the contaminant plume is flowing, and they all draw water at depths of less than 100 feet below the surface. They are therefore in danger of serious contamination by the leachate plume from Price's Pit.

The ACMUA wells pump between ten and eleven million gallons per day from September to May, and approximately fifteen million gallons per day during summer months. During 1980, over ninety percent of Atlantic City's water needs were satisfied from the wells, with the remaining ten percent coming from the reservoir In 1979, Atlantic City began to experience difficulties with the surface water provided by the reservoir: turbidity and color of the surface water would have required expensive treatment. Because this problem persists, the ACMUA has increased the use of well water and decreased its use of the reservoir. Although it is possible for the ACMUA to return to greater dependence on reservoir water, the city's present treatment facilities cannot adequately treat that water, so that greater reliance on surface water is not an option for the ACMUA.

Atlantic City has no other readily accessible alternate source of supply should these wells become contaminated. Salt water incursion and other problems prevent increased reliance on the other wells in the system. Nor does Atlantic City have a method for treating Cohansey Aquifer water on line. There are, of course, technologies for removing organic chemical contaminants from water, notably granulated activated charcoal filtration, and they could be added to the Atlantic City system at some cost.

POSTSCRIPT

On September 23, 1981, the U.S. District Court of New Jersey denied a government application for a preliminary injunction against the owner-operators of Price's Pit, the Price family and the A.G.A. Partnership which purchased the site in 1979 (U.S. versus Charles Price, 1981). The government sought two forms of injunctive relief: (a) that the defendants be required to fund a study to determine the extent of the problem posed by the leachate from the landfill, and (b) that they be required to provide an alternative water supply to those private well owners whose wells are presently contaminated. The court also denied the summary judgment motion of the defendants. The matter is still under litigation.

A study of the Cohansey Aquifer by a consulting firm (Paulus, Sokolowski, Sartor, undtated) was commissioned by the Atlantic City Municipal Water Authority (ACMWA). Included in this study is a modeling project by Dr. Gray of Princeton, and an assessment of the available data on well contamination by the O. H. Materials Co.   EPA and NJDEP are presently considering a proposal by a private developer to build a landscaped parking lot over the landfill, to be used by employees of the Atlantic City casinos. Delay in approving the request stems from fear of explosions due to the accumulation of unvented methane and other gases from ongoing chemical processes in the buried dump.

MODELING TOXICS TRANSPORT IN THE UPPER COHANSEY AQUIFER: A SEQUENCE OF
EXPERIMENTS

So much for a qualitative account of the Price's Pit episode. To go
further, and to think about what did and might have happened there in some
disciplined way, we will need a model. That model will be used to connect
releases into the Cohansey aquifer with contaminant concentrations at the
Atlantic City drinking water wells, and with human exposures to contaminants.

Begin with a look at the topography and geohydrology (figure 8).
Price's Pit sits roughly one mile west of the sites from which the Atlantic
City Municipal Water Authority pumps most of its drinking water. Those
production wells bear the generic label AC in the figure. Typically, the
wells in service pump large volumes of water--on the order of one million
gallons per day. Situated closer to the landfill, and for the most part
northeast of it, are several privately-owned water supply wells, most of
which serve one or a few families.

Suppose it were the case that the landfill was situated over an aquifer,
and that the separation between landfill and aquifer was a relatively
permeable layer. Suppose further that waste from the landfill was free to
leach into the aquifer; finally, suppose that the direction of flow in the
aquifer was eastward. Under all those conditions, toxic chemicals in the
leachate could be carried into the private and public water supply wells, and
people could be exposed to those chemicals in drinking water.

As we now know, all of these suppositions were, and are, accurately
descriptive of the Price incident. But to estimate actual or potential human
exposures requires either considerable information on, or heroic assumptions
about, the mechanism by which toxics are transported from the source of
contamination--Price's Pit, in this case--to the drinking water supply wells.
The serious and quantitative exploration of these phenomena, called
groundwater solute transport, is relatively recent. While there has been
considerable work on salinity transport, study of the more difficult cases of
nonconservative and reactive toxic groundwater contaminants is less advanced.
But several models, of varying complexity and cost, are available, and it may
be easiest to organize discussion of our own choices around a brief
discussion of some features of those models.

Were information and computation costless, we would map the aquifer in
considerable spatial detail, establishing the boundaries of the confined
layer and measuring porosities and transmissivities throughout that layer.
Using that information, we would calibrate model IV of table 14 for that
model can be used to compute the transport of groundwater contaminant in an
aquifer with arbitrary boundaries, and in a flow pattern generated by
arbitrary recharge and pumping patterns ("arbitrary" here of course means
consistent with conservation of mass and Newton's Laws).

So much for that particular straw person. Computation is not costless,
as a glance at the last column of table 14 will remind us, and "information,"
particularly on an aquifer, means drilling wells and sampling from those

wells, both expensive propositions. Given those facts of life, how shall we proceed?

There is a formal answer: statistical decision theory tells us to choose a model for computing damages by minimizing expected costs, with the relevant cost concept involving both computational and informational costs, on the one hand, and the more conventional costs associated, for example, with human health damages from the drinking of contaminated water, on the other. Within that framework, the cost of choosing a particular model must include the cost of making wrong decisions because of the simplifications and distortions associated with that model. In principle, we can ask ourselves to make subjective estimates of such costs.

Unfortunately, in practice we have almost no basis for doing so. Some such basis can, we think, only be developed by working with this class of models in a more open and experimental way, at least initially. The nature of the groundwater regime is such that even rough models can provide interesting information, for typical groundwater flow velocities are of the order of one foot per day. At such flow velocities, it takes contaminants injected into an aquifer underlying the landfill site depicted in figure 8 about five thousand days, or almost fourteen years, to reach the area to the east and south in which the production facilities are concentrated. Such sluggish systems are relatively easy to model: think, for example, of the very different surface-water flow regime, where flow velocities are four order of magnitudes higher and where those flow velocities can change by factors of ten or one hundred within a period of days.

Here then, is a plan for exploiting the groundwater models listed in table 14. We will begin by making damage estimates with transport of contaminant in groundwater-represented by the Wilson-Miller model (I). That model is an analytical, as opposed to a numerical, model. This means that it yields a closed-form expression for contaminant concentrations at any given time (after the first infiltration of leachate into the aquifer) and at any given location within the aquifer. Moreover, it allows for representation of two of the natural processes which can retard or indefinitely postpone the arrival of transported contaminant at the drinking water wells: volatization and retardation by adsorption can be represented by the choice of the retardation factor parameter.

But the Wilson-Miller model, like any analytical model, has several major defects. The first, and perhaps the most serious, is the required "distortion" of the aquifer boundaries. This is an intrinsic, as opposed to an accidental and remediable, feature of analytical models in hydrology. What makes analytical solutions possible is analytically-specified, and therefore highly idealized, boundaries. The second defect is the lack of explicit representation of the deformation of the aquifer flow pattern by pumping from the Atlantic City Municipal Authority supply wells. Return to figure 8. Pumping from municipal supply wells deforms the flow pattern, even if that flow pattern, when undisturbed, is approximately undistorted flow eastward, with the flow velocity uniform over the whole flow field.

Table 14. Groundwater Solute Transport Models

Model	Analytical or Numerical	Dimensionality	Solute Transport Included	Deformation of Flow Pattern by Dumping	Approximate Cost Per Run
I Wilson and Miller (1978)	Analytical	Two-dimensional	Explicitly	No	$5
11 Prickett and Lonnquist (1971)	Numerical (Finite Difference)	Two-dimensional	No	Yes	$20
III Wilson (1979)	Numerical (Finite Difference)	Two-dimensional	No	Yes	$50
IV Konikow and Bredehoeft (1978)	Numerical (Finite Difference)	Two-dimensional	Yes	Yes	$100

It happens to be the case that the geometry of the aquifer underlying the Price's Pit area, the Cohansey aquifer, is very close to the idealized geometry for which the Wilson-Miller analytical solution is derived. The Wilson-Miller model assumes flow in an infinite, perfectly-mixed, aquifer confined between horizontal and relatively impermeable surfaces. Fortuitously, that seems to be the configuration of the Upper Cohansey aquifer, as we shall shortly see.

But the second defect, or limitation, of the Wilson-Miller model is more serious. It does not allow for the representation of pumping; put another way, it can be expected to be very accurate only where pumping rates (from supply wells in the aquifer) are small enough, relative to flow rates, to allow neglect of pumping rates in computing contaminant concentrations.

That argument is not decisive against the Wilson-Miller model; it simply means that we should explore a range of model parameters sufficient to "cover" the effects of pumping. In fact, the Wilson-Miller model is so convenient computationally, and based upon geometric assumptions so close to those characteristic of the Cohansey aquifer, that we can make excellent use of the order-of-magnitude estimates derived from that model.

Nevertheless, we will eventially have to confirm, even at substantial additional computational cost, that those order-of-magnitude estimates are robust. To do so, we will have to compute contaminant concentrations with one or more of the models which do allow for deformation of the flow field by pumping from supply wells. Again referring to table 14, that means either the Prickett and Lonnquist (1971) model or the Konikow-Bredehoeft (1978) model. The Pricket model lacks an explicit representation of solute transport; that leaves us with the Konikow-Bredehoeft model. We note that we want to exploit that model for reasons that go well beyond checking the predictions of the Wilson-Miller model. For certain components of total damage from a groundwater Incident, there may be important interdependencies between pumping rates (from the public supply wells) and exposures: the faster water is pumped from those wells, the more rapidly contaminants are drawn into the area of the aquifer underlying the wells, and the greater the risks of human exposures. And in the months and years after contamination is discovered and recognized as a problem, some remedial measures--including pumping from the aquifer--may be feasible. Both of those effects can only be represented in a model with the features of the Konikow-Bredehoeft model.

Here, then, is a rough sketch of our strategy for modeling the Price's Pit incident, and for computing the damages associated with this and similar incidents. We will begin with the Wilson-Miller model, computing contaminant transport and damages. With the results of that computation in hand, and using those results for guidances, we will expand our damage computations, using the Konikow-Bredehoeft model, and including the effects of supply-well pumping sequences and remedial measures.

AN OVERVIEW OF THE ANALYSIS

An overview may be helpful in preparing the reader for what follows. In the Price's Pit case, the source term is, to say the least, highly uncertain:

a glance at the appendix, or a moment's reflection, is enough to emphasize how little we know about what has been accepted for disposal at the Price site, and presumably at other similar sites. In fact, we have little more than the rough listing of the kinds of chemical substances that may have been accepted. Under the circumstances, we have chosen to work backwards. We begin with observed concentrations of several chemicals at several wells close to the Price site, and then estimate the source term that would have been required to generate those observations. All of this, together with many qualifications, is found in the section on Adaptation of the Wilson-Miller Model of chapter 6, and in the appendix.

In the course of that estimation exercise, we will have already used a particular transport model: given those source-term estimates, we again invoke that model to estimate time profiles of exposure (to chemical contaminants in drinking water) at particular wells. The model used, and the model parameters selected, are discussed in the Monetary Benefit Estimates section of chapter 6. The ambient concentrations computed, for particular wells drawing on the Cohansey aquifer and for particular times, are described in previously mentioned section on the Adaptation of the Wilson-Miller Model. Finally, taken together with dose-response and value of risk factors, we are able to produce cost of human health risk estimates: those are given in the Monetary Benefit Estimates section of chapter 6.

NOTES

[1] Outlined in EPA's <u>Methods for Chemical Analysis for Water and Wastes</u> and in <u>Sampling and Analysis Procedure for Screening of Industrial Effluents for Priority Pollutants</u>.

[2] <u>Federal Register</u>, November 28. 1980.

CHAPTER 6

THE BENEFITS OF AVOIDING A PRICE'S PIT-TYPE INCIDENT

INTRODUCTION

Figure 9 is a schematic of the Price site topography and geohydrology: it is a caricature to aid visualization, and not a scale drawing. A little reflection on that topography and geohydrology suggests why what did happen might have been expected to happen. Rainwater will eventually leach toxic chemicals and heavy metals from the waste in the landfilled ground. Those leached wastes--or leachate--will ultimately seep into groundwater, first encountering the upper unsaturated groundwater zone and ultimately entering the zone in which there is very little air mixed with the water and sand--the "saturated zone," or aquifer. And because the aquifer flows toward the Atlantic City drinking water wells (and other drinking water wells in the area), that contamination may ultimately affect drinking water supplies.

Note that, in figure 9, there are several saturated layers, or aquifers: an upper layer, appropriately called the Upper Cohansey aquifer, is separated by a relatively impermeable clay layer (or aquitard) from the Lower Cohansey aquifer. In fact, drinking water wells in the Price's Pit area draw upon both Upper and Lower Cohansey aquifers for their supplies. Contamination in the upper aquifer may or may not enter the lower aquifer, depending upon the permeability and extent of the separating layer.

We now know that the clay separating layer separating the upper and lower aquifers is relatively impermeable. But while this, and other features of the Price area geohydrology, are critical for planning remedial measures at that site, our aim here is damage estimation. From that vantage point, geohydrological uncertainty is only one more kind of uncertainty. So let us set out a framework for damage estimation.

Figure 10 is the lottery that might have been constructed ex ante by a land-use planner contemplating the licensing of landfill operations at Price's Pit. Leaching might, or might not, have occurred: had the Pit been properly lined, the incident might have been avoided. In the event of leaching, contamination of the upper aquifer might have been detected long before drinking water supplies became contaminated. In that event, remedial measures to protect the city drinking water supply wells might have been taken. Among those measures are pumping and recharge operations to limit the spread of the leachate plume toward the aquifer, or the resort to alternative (and presumably more expensive) sources of drinking water.

y

Drinking Water Wells

Coordinate Grid for Two-dimensional
Solute-transport Models

Drinking Water Wells

← Price's
Pit Landfill

x

Upper Aquifer

Lower Aquifer

Leachate from →
Landfill
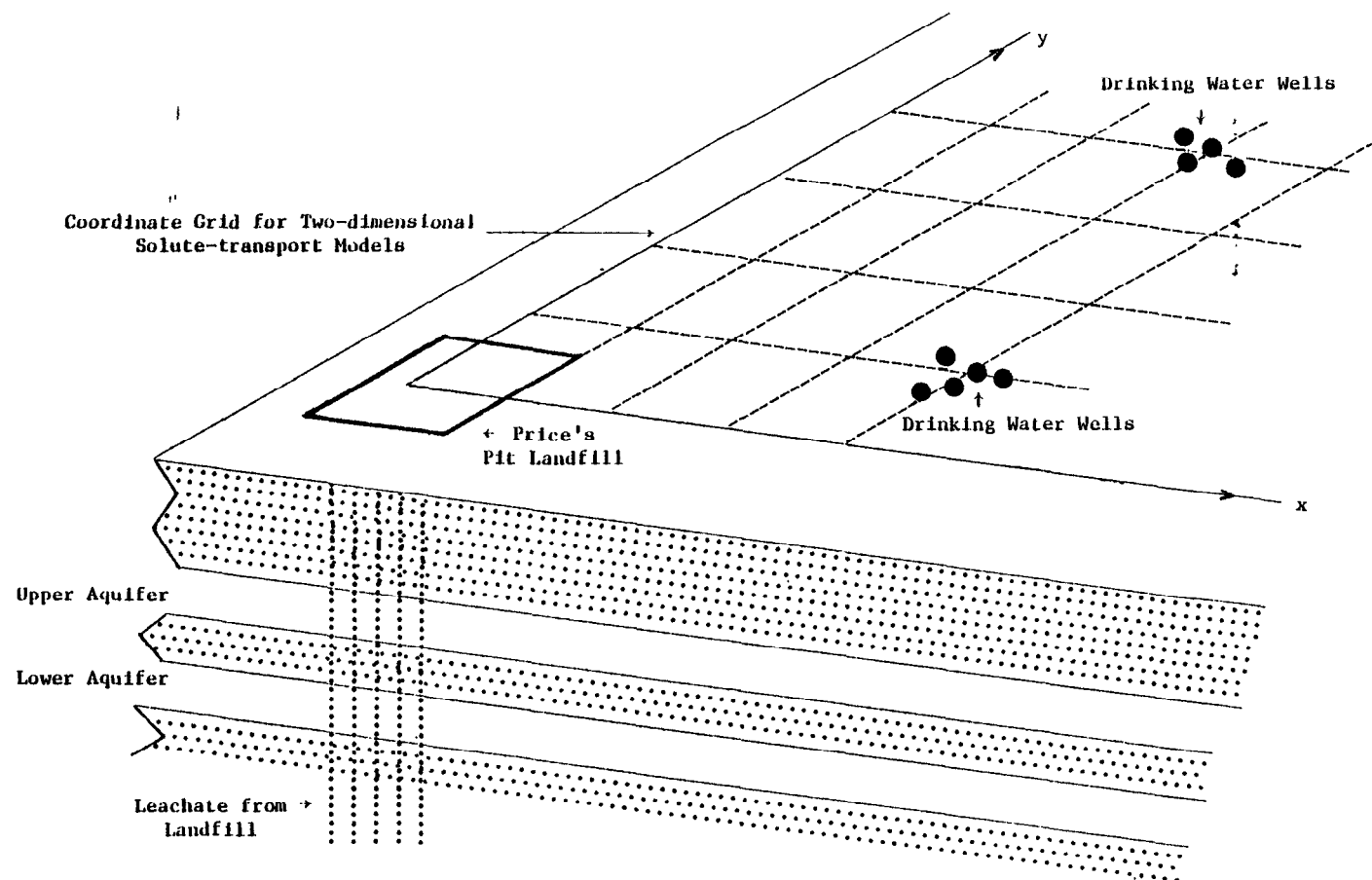
Figure 9. A Simplified Price's Pit Geohydrology and Geography

Figure 10. The Price's Pit Incident Lottery

P   CHANCE NODE

D   DECISION NODE

C   CONSEQUENCE
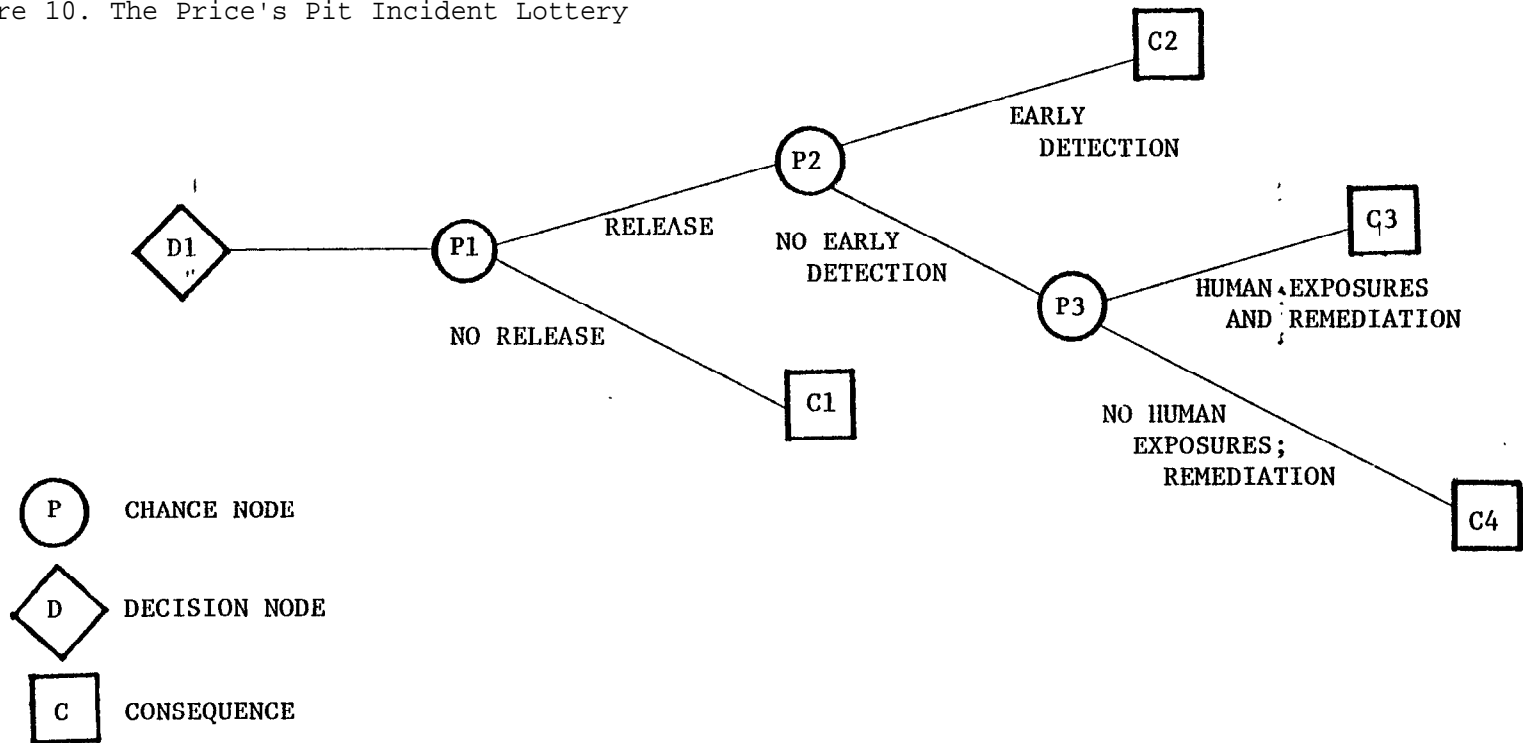
D1:   Lottery accepted; landfill sited

P1:   Release sublottery

C1:   No release from landfill

P2:   Early detection sublottery

C2:   Early remediation (or substitution of alternative water supplies)

P3:   Human exposures sublottery

C3:   Human exposures and remediation

C4:   No human exposures

If contamination of the upper aquifer went undetected for some period, human exposures to contaminants in drinking water would have extended over the period between the time at which contaminants reach wells to the time at which wells are closed for drinking. Along this branch of the tree of figure 10, both the costs of those human exposures and the costs of required remedial measures would be incurred.

We can now describe our framework for damage estimation: we will estimate the cost of bearing the lottery depicted in figure 10, and then identify that cost with the benefits of a policy which might have prevented a Price's Pit type incident. The principal damage component we will estimate, in what follows, is the human health damage component. To do so, we need a way of translating the first event in the tree--releases of leachate from the landfill and into the aquifer--into contaminant concentrations at the wells. In other words, we need a model of contaminant transport in groundwater.

ADAPTATION OF THE WILSON-MILLER MODEL

For the reasons given in chapter 5, we begin with the analytical model of groundwater solute transport derived by Wilson and Miller (1978). That model is a two-dimensional, vertically-averaged model of contaminant transport in an infinite aquifer with plane-parallel confining boundaries. Specifically, if at time zero some particular contaminant begins to leach into the aquifer at a rate of f_m pounds per day, then contaminant concentration at point (x, y) in the aquifer, and at time t, c(x, y, t), is given by:

$$c(x,\ y,\ t)\ =\ \frac{1.603\ \text{x}\ 10^{+4}}{m}\left(\frac{f_m'\ \exp\frac{x}{B}}{4\pi n(D_x D_y)^{\frac{1}{2}}}\right)W(u, \qquad\qquad (6.1)$$

in which

$$D_x\ =\ \alpha_x V$$

$$D_y\ =\ \alpha_y V$$

$$B\ =\ 2D_x/V \qquad\qquad\qquad (6.2)$$

$$=\ 1\ +\ (2B/V)$$

$$r\ =\ [(x^2\ +\ y^2 D_x/D_y)]^{\frac{1}{2}}$$

$$W(u,\ \frac{r}{B})\ =\ (\frac{\pi B}{B})^{1/2}\ \exp(-\frac{r}{2r})\ \text{erfc}\left(\frac{\frac{r}{B}\ -2u}{2u^{1/2}}\right) \qquad\qquad (6.3)$$

Here erfc is the complementary error function, defined in terms of the error function

$$\text{erf}(\beta) = \frac{2}{\pi} \int_0^{\beta} e^{-\varepsilon^2} d^2$$

by the equation

$$\text{erfc}(\beta) = 1 - \text{erf}(\beta)$$

Moreover, the retardation-adjusted dispersivities and velocity are defined, in terms of the unadjusted dispersivities and velocity, by

$$D_x' = D_x/R_t$$

$$D_y' = D_y/R_t \qquad\qquad (6.4)$$

$$V' = V/R_t$$

The variables appearing in equation (6.1), and their units and typical ranges, are summarized in table 15 below. In that table we list both the original parameter names and the corresponding names in our FORTRAN implementation of the Wilson-Miller model. Our list is shortened by an assumption: we take the Upper Cohansey aquifer in our didactic Price's Pit incident to be spatially homogeneous, so that dispersivities in the x and y (directions) are equal.

More important than any very detailed understanding of the derivation of equation (6.1) is some rough understanding of how that solution is likely to depend upon a few key parameters and variables. For, like any model of a complicated real-world geohydrology, this one is an approximation, capable at best of giving us good order of magnitude estimates of contaminant concentrations. The key parameters for our purposes are f_m' (SOURCE), m (TRICK), v (VEL), and n (POR). From equation (6.1), note that concentrations are linear in f_m': the Wilson-Miller model assumes contaminant inflow (into the aquifer) at a constant rate, beginning at time zero, and proportional to f_m'. Next note that the parameter m (TRICK) is a constant because of the assumption (underlying the Wilson-Miller model) that the aquifer boundaries are infinite parallel planes: that assumption happens, fortuitously, to be a good representation of what we know of the Upper Cohansey aquifer in the Price's Pit area. The parameter velocity v (VEL) is a constant under the model assumption of constant aquifer flow velocity in the x direction: this may be a good approximation to the flow pattern in the Cohansey aquifer in a low-pumping regime, but cannot be expected to be much better than an order-of-magnitude approximation when pumping rates are high. Finally, the porosity n (POR) tells us what fraction of the aquifer consists of voids through which water can travel. For a homogeneous aquifer, which the Upper Cohansey seems to approximate, porosity is relatively easy to measure.

NOW let US begin our exploration of one branch of the Price's Pit lottery of figure 10. The particular branch we want to explore, with the help of the Wilson-Miller model, is one along which individuals are exposed to toxic chemicals present at relatively low concentrations in drinking water. In the actual Price's Pit topography (figure 9), numerous private

Table 15. Variables and Units for an Implementation of the Wilson-Miller
             (1978) Solute Transport Model

	FORTRAN Parameter (Original Name)	Unit	Meaning	Assumed Value
Aquifer-Specific Parameters	THICK (m)	Feet	Thickness of Upper Aquifer	50 feet
	VEL (v)	Feet/day	Aquifer flow	1 ft/day
	POR (n)	Pure Number	Aquifer Porposity	0.3
Pollutant-Specific Parameters	SOURCE (f'_n)	Pounds/day	Mass Pollutant	(Benzene) 7,700 lbs/day
	A (α)	Feet	Longitudinal (and Horizontal) Dispersivity	100 feet
	R (R_t)	Pure Number	Retardation Factor	1.0
Model Run-Specific Parameters	SX, SY	Feet	Space Grid Step Size	N.A.
	ST	Days	Time Step Size	1 year

drinking wells stand between the landfill site and the Atlantic city Municipal Water Authority supply wells. Because contaminant concentrations reached high levels in the private wells, the existence of a problem was recognized long before contamination of the Atlantic City public supply wells posed a threat to human health. The long lag between recognition and public supply-well contamination is a simple consequence of the low (advective) transport velocities characteristic of groundwater flows.

But not all sites will share the particular feature that led to early recognition of the difficulties a Price's Pit. Thus the lottery of figure 10 includes branches along which such recognition does not occur. Indeed, the principal damage contribution may lie along a branch for which recognition occurs only after there have been substantial human exposures. That can happen because concentrations at the parts per billion level are difficult to detect, even with the current tool kit of field-grade analytical chemistry.

For an idea of how gradually contaminant concentrations in drinking water can increase even when leaching rates into an aquifer are very high, consider tables 16 and 17. Both have been calculated, from the Wilson-Miller model, for a "reference" source of contaminant equal to the injection of 0.1 pounds per day into the aquifer near the origin of the coordinate grid, the location of the landfill. Note that even at the Johnson well site, situated at coordinates (400, 900) feet from the center of the landfill, the buildup of contaminant concentration is remarkably slow: at ten years (or 3,650 days) after contamination begins, the ambient concentrations at the Johnson well site is only 6.45 parts per billion. The concentrations at the production well called AC-2, which is located at coordinates (4850, 1850), are of course considerably smaller. Note that a level of greater than 6 parts per billion is reached only after about twenty years.

This remarkably slow buildup of contaminant concentration gives rise to the branch of the Price lottery tree that may contribute the highest, damage component: the branch along which there are long-term, unrecognized, low-level exposures. The computation of those exposures is, in principle, fairly routine, and involves the following steps. First, for each chemical, we use actual observations on that chemical at wells near the Price site to calibrate the Wilson-Miller model. That amounts to fixing the only free parameter, the source term. Then we compute a time profile of exposures from all wells, extending over the period between the time at which the aquifer is first contaminated to the time at which drinking water from the aquifer is prohibited. In a moment we will present the results of that calculation; before we do, we warn that things are not as simple as they seem. In particular, we really know very little about the source term, and the leap from the data evidence--the concentrations of contaminants observed in wells around the Price's Pit area--is a long one. In using the Wilson-Miller model to reconstruct an exposure time profile, we are assuming that contaminant leaches into the aquifer at a constant rate. This may be approximately true for some contaminants, but for others it will almost certainly be true that releases into the aquifer will be intermittent, giving rise to "slugs"--regions of the aquifer bearing substantial amounts of some contaminants, and advected by groundwater. Such slugs may pass well screens, temporarily polluting water drawn from those wells, and then pass on.

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Table 16.   Contaminant Concentration at Johnson Well Versus Time for
            Reference Source of 0.1 Pounds Per Day

Time (Days)	Contaminant Concentration (Parts Per Billion)
365	0.056
730	1.301
1,085	3.058
1,460	4.178
1,825	4.739
2,190	5.024
2,555	5.235
2,920	5.490
3,285	5.870
3,650	6.445
4,015	7.299
4,380	8.550
4,745	10.377
5,110	13.068
5,475	17.099
5,840	23.268
6,205	32.970
6,570	48.707
6,935	75.122
7,300	121.166

Table 17. Calculated Contaminant Concentration at Atlantic City Well AC-2
Versus Time, for Reference Source of 0.1 Pounds Per Day

Time (Days)	Contaminant Concentration (Parts Per Billion)
356	0.000
730	0.000
1,095	0.000
1,460	0.000
1,825	0.000
2,190	0.000
2,555	0.000
2,920	0.011
3,285	0.071
3,650	0.271
4,015	0.721
4,380	1.470
4,745	2.463
5,110	3.563
5,475	4.620
5,840	5.524
6,205	6.230
6,570	6.741
2,935	7.098
7,300	7.352
7,665	7.558
8,030	7.766
8,395	8.022
8,760	8.368
9,125	8.850
9,490	9.517
9,855	10.436
10,220	11.694
10,585	13.416
10,950	15,786
11,315	19.078
11,680	23.716
12,045	30.367
12,410	40.104
12,775	54.702
13,140	77.173
13,505	112.777

Sometime we hope to do a calculation of exposures from such slugs; for now, we return to the more tractable situation in which continuous injection of contaminant into the aquifer at a constant rate is assumed. To some extent, we "eliminate" slug phenomena by including in this first calculation only those contaminants observed at several wells. If a contaminant is observed at many wells, some of which are separated by several hundred feet, then there very likely is a contaminant plume spreading. Of the 129 priority pollutants whose concentrations were measured at Price's Pit and in the surrounding wells, at least those listed in table 18 seem to fit this picture of plume transport.

For the chemicals listed in table 18, the source term in the Wilson-Miller model has been calibrated by assuming that the concentration observed at the indicated well represents the ten-year concentration reached at that well. The corresponding source terms are listed in the last column of that table. Those numbers indicate how many pounds per day of the contaminant in question must enter the aquifer in order to produce the indicated concentration.

Given that source term, we can compute concentrations, at any well drawing on the aquifer, for any time after contaminant enters the aquifer. We have computed those concentrations for the wells from which the Atlantic City Municipal Water Authority pumps its water, and for the Johnson wells, for all of the chemicals listed in table 18. The results are exhibited for two arbitrarily chosen chemicals (4, benzene, and 68, Di-n-butyl Phthalate), in tables 19 and 20. In each table the concentrations of the chemical in question are given, by well and time: concentrations are in parts per billion, and time is given in one-year intervals, from year one (365 days) to year 20 (7,300 days). For example, water drawn from well AC2 one year after the first seepage of leachate into the Upper Cohansey aquifer has 0.170×10^{-37} parts per billion of benzene (effectively no benzene), but that concentration builds up to 2.1 parts per billion in year 10.

Then, by combining those computed concentrations with our exposure and dose-response assumptions, we can calculate incremental individual annual mortality risks per year over the remaining lifetime after the twenty-year exposure. Since we have high and low toxicities bounding the "true" dose-response function, we report the corresponding high and low incremental individual risks. Again, we emphasize that the reported figures are annual incremental mortality.

There is a small, two-entry column, headed "risk," in both tables 19 and 20. Those entries are population-risk aggregates, with the population at risk, about 40,000 individuals, exposed over the twenty-year period to a production-weighted average benzene concentration. The weights are of course the shares of the individual drinking water supply wells in total production. Finally, note that the low and high risk figures differ for benzene in table 19, but are identical for di-n-butyl phthalate in table 20. This is because the low and high toxicity estimates for the latter chemical are essentially identical, implying considerable scientific confidence in that number. But the low and high estimates for benzene differ by about a factor of three,

Table 18. Suspected Contaminants, Upper Cohansey Aquifer Plume From Price's Landfill;
Concentrations in Parts Per Billion

Chem. #	Chemical	LOTOX	HITOX	Well Selected	Observed Concentration At Well	Impute Source, in Pounds Per Day
(4)	Benzene	6.6	2.3	JOHNSON2	48.0	.745
(7)	(Mono) Chlorobenzene	488.0	20.0	EPA1A	27.0	.055
(10)	1-2-Dichlorobenzene	9.4	9.1	JOHNSON	20.0	.310
(13)	1-1-Dichloroethane	0.066	0.066	EPA1A	53.0	.108
(23)	Chloroform (Trichloromethane)	2.4	1.9	EPA1A	68.0	.138
(44)	Halomethanes	1.9	1.9	JOHNSON2	15.0	.233
(68)	Di-n-butyl Phthalate	3,000.0	3,000.0	EPA1A	16.0	.033
(87)	Trichloroethylene	33.0	27.0	C6	12.0	.143
(88)	Vinyl Chloride	20.0	2.4	EPA1A	76.0	.155

Table 19. Benezene Concentrations[1] Versus Time and Aggregate Incremental Mortality Risk[2], Atlantic City Production Wells and Johnson Well

	RISK	AC2	AC4	AC8	AC13	JOHNSON
LOW RISK	0.104E+02	0.155E-03	0.161E-03	0.222E-03	0.474E-03	0.134E-02
HIGH RSK	0.300E+02	0.444E-03	0.462E-03	0.636E-03	0.136E-02	0.384E-02
CONCENTR AT 365.		0.170E-37	0.244E-35	0.233E-39	0.158E-26	0.435E+00
CONCENTR AT 730.		0.103E-22	0.984E-21	0.166E-23	0.394E-13	0.101E+02
CONCENTR AT 1095.		0.194E-14	0.941E-13	0.417E-15	0.962E-07	0.237E+02
CONCENTR AT 1460.		0.331E-09	0.734E-08	0.101E-09	0.264E-03	0.323E+02
CONCENTR AT 1825.		0.835E-06	0.964E-05	0.377E-06	0.265E-01	0.367E+02
CONCENTR AT 2190.		0.176E-03	0.109E-02	0.995E-04	0.465E+00	0.389E+02
CONCENTR AT 2555.		0.672E-02	0.268E-01	0.474E-02	0.299E+01	0.405E+02
CONCENTR AT 2920.		0.874E-01	0.250E+00	0.730E-01	0.103E+02	0.425E+02
CONCENTR AT 3285.		0.552E+00	0.122E+01	0.526E+00	0.237E+02	0.454E+02
CONCENTR AT 3650.		0.210E+01	0.381E+01	0.222E+01	0.415E+02	0.499E+02
CONCENTR AT 4015.		0.558E+01	0.865E+01	0.641E+01	0.602E+02	0.565E+02
CONCENTR AT 4380.		0.114E+02	0.156E+02	0.140E+02	0.769E+02	0.662E+02
CONCENTR AT 4745.		0.191E+02	0.236E+02	0.247E+02	0.898E+02	0.803E+02
CONCENTR AT 5110.		0.276E+02	0.315E+02	0.372E+02	0.989E+02	0.101E+03
CONCENTR AT 5475.		0.358E+02	0.385E+02	0.499E+02	0.105E+03	0.132E+03
CONCENTR AT 5840.		0.428E+02	0.439E+02	0.613E+02	0.109E+03	0.130E+03
CONCENTR AT 6205.		0.482E+02	0.479E+02	0.705E+02	0.112E+03	0.255E+03
CONCENTR AT 6570.		0.522E+02	0.506E+02	0.773E+02	0.116E+03	0.377E+03
CONCENTR AT 6935.		0.550E+02	0.526E+02	0.822E+02	0.120E+03	0.532E+03
CONCENTR AT 7300.		0.569E+02	0.541E+02	0.856E+02	0.127E+03	0.738E+03

Notes for Table 19:

(1) Concentrations in parts per billion.

(2) Aggregate incremental mortality risk is individual incremental mortality risk times the population at risk.

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Table 20. Di-n-butyl Phthalate Concentrations[1] Versus Time and Aggregate Incremental Mortality Risk[2], Atlantic City Production Wells and Johnson Well

	RISK	AC2	AC4	AC8	AC13	JOHNSON
LOW RISK	0.966E-03	0.143E-07	0.149F-07	0.205E-07	0.438F-07	0.124E-06
HIGH RSK	0.966F-03	0.143E-07	0.149E-07	0.205E-07	0.438F-07	0.124E-06
CONCENTR AT 365.	0.713E-39	0.103E-36	0.979E-40	0.664E-28	0.183E-01
CONCENTR AT 730.	0.433E-24	0.414E-22	0.698E-25	0.165E-14	0.424E+00
CONCENTR AT 1095.	0.817E-16	0.396E-14	0.175E-16	0.405F-08	0.396E+00
CONCENTR AT 1460.	0.139E-10	0.309E-09	0.423E-11	0.111F-04	0.136E+01
CONCENTR AT 1825.	0.372E-07	0.405E-06	0.159E-07	0.112E-02	0.154E+01
CONCENTR AT 2190.	0.741E-05	0.456E-04	0.418E-05	0.196F-01	0.164E+01
CONCENTR AT 2555.	0.283E-03	0.113E-02	0.199E-03	0.126E+00	0.170E+01
CONCENTR AT 2920.	0.368E-02	0.105E-01	0.307E-02	0.433E+00	0.179E+01
CONCENTR AT 3285.	0.232E-01	0.514E-01	0.221E-01	0.996F+00	0.191E+01
CONCENTR AT 3650.	0.884E-01	0.160E+00	0.934E-01	0.174F+01	0.210E+01
CONCENTR AT 4015.	0.235E+00	0.364E+00	0.270E+00	0.253F+01	0.238E+01
CONCENTR AT 4380.	0.479E+00	0.654E+00	0.587E+00	0.323F+01	0.270E+01
CONCENTR AT 4745.	0.802E+00	0.992E+00	0.104E+01	0.378E+01	0.338E+01
CONCENTR AT 5110.	0.116E+01	0.133E+01	0.157E+01	0.416E+01	0.425E+01
CONCENTR AT 5475.	0.150E+01	0.162E+01	0.210E+01	0.441F+01	0.557E+01
CONCENTR AT 5840.	0.180E+01	0.195E+01	0.258E+01	0.459E+01	0.757E+01
CONCENTR AT 6205.	0.203E+01	0.201E+01	0.296E+01	0.473F+01	0.107E+02
CONCENTR AT 6570.	0.219E+01	0.213E+01	0.325E+01	0.487E+01	0.159E+02
CONCENTR AT 6935.	0.231E+01	0.221E+01	0.346E+01	0.505E+01	0.245E+02
CONCENTR AT 7300.	0.239E+01	0.227F+01	0.360E+01	0.532F+01	0.394E+02

Notes for Table 29:

(1) Concentrations in parts per billion.

(2) Aggregate incremental mortality risk is individual incremental mortality risk times the population at risk.

accounting for the spread between the corresponding low and high risk estimates.

In table 21, we bring together all low and high risk estimates for all chemicals and all wells. And by taking the production-weighted well concentrations, multiplying by the population at risk, and summing over wells, we arrive at low and high estimates for total annual incremental mortality risk. Again, those figures represent increments, over the population at risk, in mortality risk per year. The low figure is $0.17 \times 10^{+3}$, and the high figure $0.202 \times 10^{+3}$.

MONETARY BENEFIT ESTIMATES

From those aggregate annual mortality risk estimates, a simple multiplication by the value of incremental mortality risk gives us the "unweighted" cost of bearing the risk associated with the lottery. Those multiplications are done, and the results summarized for inspection, in table 22. For illustrative purposes, let us focus on a particular set of values that we find reasonable: those corresponding to the value $\$1.00 \times 10^{+5}$ for incremental annual mortality risk. With that value, the range of unweighted costs of risk bearing lies between $\$0.17 \times 10^{+8}$ and $\$0.202 \times 10^{+8}$.

Those values must be weighted by release probabilities to arrive at the standard method estimate of the cost of bearing the risk associated with the Price's Pit lottery. Let us take, for illustrative purposes, the relatively high figure of 10^{-3} for the relevant event: remembering that the event is "contamination of drinking water supplies, without detection and with human exposures through drinking water, for many years," the reader will perhaps agree that 10^{-3} is a high subjective probability. Then the release-probability weighted estimates of the cost of risk bearing lie between $\$0.17 \times 10^{+5}$ and $\$0.202 \times 10^{+5}$. Annual expenditures this large would be warranted, under the standard theory of the cost of risk bearing, if they can prevent a Price's Pit-type incident. Discounting that stream of expenditures at 10%, a capital expenditure of about two million dollars would be justified if it could, with certainty, prevent. such an incident.

IMPLICATIONS AND CONCLUSIONS

In closing our analysis of this incident, let us reemphasize the many assumptions upon which our work depends. Particularly important are our assumptions about the source term, and our related method for computing human health exposures from that imputed source term. As we have emphasized in the above two chapters, there are many more contaminants than the ones for which we have imputed sources, and then human exposures. In fact, the contaminants we have worked with are precisely those whose concentrations, over time and over wells, seem consistent with the story we have told of steady infiltration into the aquifer, at a constant rate.

But those are only a fraction of the contaminants detected at many places in the Cohansey aquifer during the sampling program. The others behave in ways suggesting that they are moving through the aquifer in slugs, i.e., as localized areas of contamination. Needless to say, exposure to

Table 21. Incremental Individual Mortality Risks by Chemical and Well

Chemical Number	Name	Well AC2	AC4	AC8	AC13	JOHNSON
(4)	Benzene	0.155×10^{-3} 0.444×10^{-3}	0.161×10^{-3} 0.462×10^{-3}	0.222×10^{-3} 0.636×10^{-3}	0.474×10^{-3} 0.136×10^{-2}	0.134×10^{-2} 0.384×10^{-2}
(7)	(Mono) Chlorobenzene	0.148×10^{-6} 0.362×10^{-5}	0.155×10^{-6} 0.377×10^{-5}	0.213×10^{-6} 0.519×10^{-5}	0.454×10^{-6} 0.111×10^{-4}	0.128×10^{-5} 0.313×10^{-4}
(10)	1-2-Dichlorobenzene	0.435×10^{-4} 0.449×10^{-4}	0.453×10^{-4} 0.468×10^{-4}	0.623×10^{-4} 0.644×10^{-4}	0.133×10^{-3} 0.138×10^{-3}	0.376×10^{-3} 0.388×10^{-3}
(13)	1-1-Dichloroethane	0.215×10^{-2} 0.215×10^{-2}	0.224×10^{-2} 0.224×10^{-2}	0.309×10^{-2} 0.309×10^{-2}	0.660×10^{-2} 0.660×10^{-2}	0.186×10^{-1} 0.186×10^{-1}
(23)	Chloroform (Trichloromethane)	0.760×10^{-4} 0.960×10^{-4}	0.792×10^{-4} 0.100×10^{-3}	0.109×10^{-3} 0.138×10^{-3}	0.233×10^{-3} 0.294×10^{-3}	0.657×10^{-3} 0.830×10^{-3}
(44)	Halomethanes	0.161×10^{-3} 0.161×10^{-3}	0.168×10^{-3} 0.168×10^{-3}	0.231×10^{-3} 0.231×10^{-3}	0.494×10^{-3} 0.494×10^{-3}	0.140×10^{-2} 0.140×10^{-2}
(68)	Di-n-butyl Phthalate	0.143×10^{-7} 0.144×10^{-7}	0.149×10^{-7} 0.149×10^{-7}	0.205×10^{-7} 0.205×10^{-7}	0.438×10^{-7} 0.143×10^{-7}	0.124×10^{-6} 0.124×10^{-6}
(87)	Trichloroethylene	0.573×10^{-5} 0.700×10^{-5}	0.597×10^{-5} 0.729×10^{-5}	0.821×10^{-5} 0.100×10^{-4}	0.175×10^{-4} 0.214×10^{-4}	0.495×10^{-4} 0.605×10^{-5}
(88)	Vinyl Chloride	0.102×10^{-4} 0.849×10^{-4}	0.106×10^{-4} 0.885×10^{-4}	0.146×10^{-4} 0.122×10^{-3}	0.312×10^{-4} 0.260×10^{-3}	0.881×10^{-4} 0.734×10^{-3}

Table 22. Unweighted Costs of Risk Bearing, Price's Pit Lottery

	Unweighted Cost of Risk Bearing	
Value of Risk	Low	High
10^{+4}	0.17×10^{7}	0.202×10^{7}
10^{+5}	0.17×10^{8}	0.202×10^{8}
10^{+6}	0.17×10^{9}	0.202×10^{9}

contaminants via well water drawn while a slug is passing the well screen can be hazardous to your health. Our neglect, on the grounds of computational difficulty, of all these contaminants moving in slugs virtually guarantees that our health effect estimates are serious underestimates.

That argument further highlights the significance of our rather large cost of risk estimates. Taken at face value, those estimates would justify substantial expenditures on monitoring to insure against long-term exposures to contaminants in drinking water drawn from aquifers. In effect, such a program would be a way of buying reductions in the probability of an episode of this kind. From our calculations, it is in fact very easy to reconstruct an imputed willingness to pay for reductions in the probability of an episode of this kind. Release probabilities are, as we have argued in chapter 2, both difficult at best and subject to enormous subjective variation at worst. For that reason, couching our results in this form may make them more useful to planning commissions or boards charged with facility citing conditions. In siting waste disposal facilities, the important question about any particular condition or provision is how much safety we are buying, and at what price.

CHAPTER 7

THE CHEMICAL CONTROL INCIDENT

THE INCIDENT

On April 21, 1980, an explosive fire at the Chemical Control
Corporation's Elizabeth, New Jersey hazardous waste treatment facility sent a
toxic mixture of gases and chemical particulates into the atmosphere.
Fifty-five gallon drums containing a variety of chemicals rocketed two
hundred feet in the air before they burst due to the intense heat.
Temperatures reached 3,000° F., melting and fusing containers. An estimated
50,000 drums of hazardous waste burned for more than ten hours before the
Elizabeth fire department was able to bring the fire under control at 9:15
a.m. During the fire, a plume of noxious smoke and ash blanketed a fifteen
square-mile area northeast from the site. Concern over the possible health
effects of exposure to contaminants in the plume prompted the New Jersey
Department of Environmental Protection to issue an advisory urging residents
to stay indoors. The plume from the fire threatened to expose 15 million
residents of New Jersey and New York City to noxious smoke. (Figure 11 shows
the area at risk within twenty kilometers of the Chemical Control site.)
Many believed that only favorable atmospheric conditions, tending to direct
the contaminants over waterways, prevented a much more serious incident.

Chemical Control, incorporated as a "hazardous waste treatment
facility," charged other firms $50 to $200 a drum to accept their dangerous
wastes for incineration. In 1972, the company was given a five-year
operating permit when its incinerator passed state air quality tests. After
a few years of operation, the efficiency of the incinerator declined, and the
contracted barrels of waste began accumulating on the site. During 1976 and
1977, Chemical Control's owner-operator, William Carracino, apparently began
"midnight dumpings" of the hazardous wastes around the city to help offset
the buildup of inventory at the site. The state attorney general's
investigation of, the alleged dumpings led to Carracino's indictment and
conviction. In 1977, he was sentenced to two consecutive three-year terms
and fined a sum of $21,000. The company pleaded guilty to the charge of
operating without all necessary permits and was fined to $75,000.[1] In 1980,
a three-judge panel refused, on appeal, to overturn the three-year term to be
served by Carracino (Sullivan, 1980).

At the time of his indictment, Carracino sold Chemical Control to Eugene
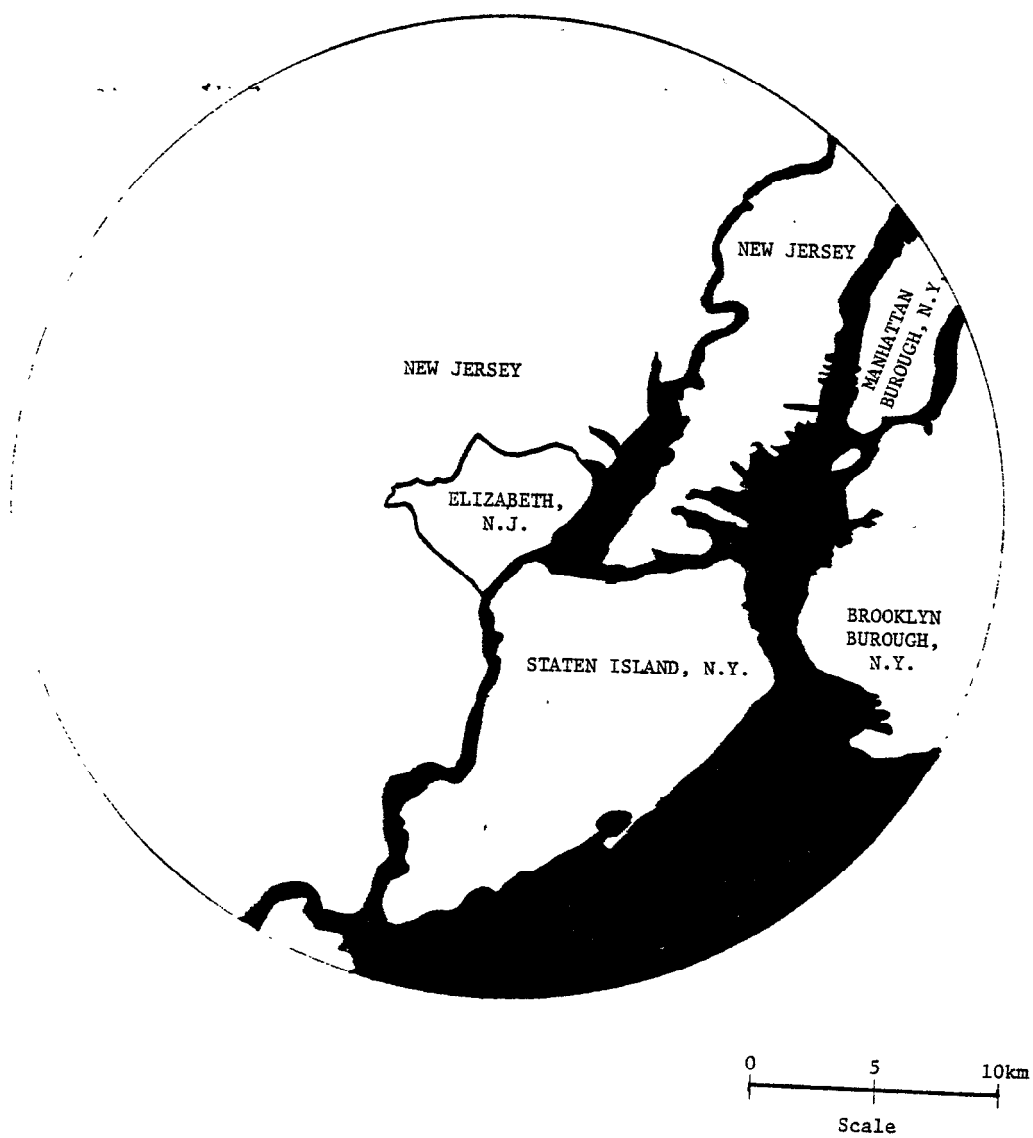Conlon and John Albert. They in turn appointed William Colleton as the new

Figure 11. Map of 20-Kilometer Area Surrounding Elizabeth, New Jersey

president.   When Colleton took over Chemical Control, there were more than 30,000 barrels stacked haphazardly across the site extending all the way out to the Elizabeth River (Weinberg, 1980).   The state administrator of Solid Waste required the new owner (1) to eliminate the barrels that had built up on the site at a rate of 1,200 per month, (Weinberg), (2) to inventory and label all on-site drums, and (3) to incinerate all burnable waste.   But the administrative order did not bar the acceptance of further contracted wastes.

The New. Jersey- Bureau of Hazardous Wastes investigated the Chemical Control site in January of 1979 and found that the new owner had failed to comply with the aforementioned agreement, and had compounded the problem by expanding the inventory to over 50,000 drums (Regenstein, 1982).   Those drums were stacked four and five high; many were rusty and leaking.   Drums containing chemicals that would react explosively with one another were stacked together.   The site was recognized as an explosion hazard a year before the incident occurred.   "Health officials reported that enough poisons and pesticides had been noted on the premises to provide a minimum lethal dose to all of Staten Island and lower Manhatten in the event of a fire at Chemical Control Corporation" (Raab, 1980).   In 1979, Carracino admitted that the site contained one thousand 55-gallon drums laden with dioxin.   In its pure form, three ounces of dioxin in New York's water supply could kill everyone in the city (Nordland & Friedman, 1979).

The Bureau of Hazardous Waste's investigation led to the suit filed against Chemical Control and its parent company, the Northern Pollution Control Company of New York.   The owners of Chemical Control, Conlon and Albert, claimed that their company did not have sufficient funds to perform a cleanup.   The Chemical Control records at the time showed only a few thousand dollars, so the state put the company in receivership (Weinberg, 1980).[2]

The Chemical Control site was condemned in 1979, and a private contractor, Peabody Coastal Services, was hired to clean up the area. Between 8,000 and 10,000 barrels of highly toxic and explosive substances were removed prior to the fire.   Within the first three and a half months of the operation, 5 pounds of radioactive substances, 10 pounds of disease-bearing material, and nearly 400 pounds of explosive material were removed.   The explosives alone would have been enough to demolish the building complex area, and could. have demolished and ignited nearby petroleum tank cars (Birns, 1979).   Many of the acutely toxic chemicals--including benzene, cyanide, military nerve gas, PCB's and nitroglycerine--were removed prior to the fire.   Financed by the New Jersey Spill Compensation Fund, the costs of this operation ranged between $11 and $13 million.

Although 8,000 to 10,000 drums of the most hazardous of materials were removed prior to the April 1980 fire, an estimated 50,000 barrels remained at the site.   The chemicals known to be at the site during the fire included insecticides, mercury compounds, nitric and picric acids, benzene, toulene, solvents, plasticizers, alcohol, and ethylene dichloride.   There is no quantity inventory, however, of those substances; that makes assessment of health damages from inhalation of toxic fumes difficult. It is possible that

the intense heat of the fire may have neutralized some of the chemicals. On the other hand, many firefighters, bystanders, and residents as far away as Staten Island required treatment for irritated throats, eyes, lips, and skin. Some also suffered temporary loss of appetite, vomiting, diarrhea, and eye strain. Fire fighters and waste disposal workers were reported to be still suffering from dizziness and diarrhea six months after the fire (Regenstein, 1982).   The chronic effects of toxic and carcinogenic exposures may take decades to show up, and are therefore not likely to be attributed to the Chemical Control fire

New Jersey officials claimed that there was virtually no measurable contamination near the site following the fire, and air samples taken during the fire in fact showed ambient concentrations of the sampled chemicals to be well below federal limits for exposures over an eight-hour **period.**[3] On the other hand, many toxic chemicals, including benzene, toulene, chloroform, carbon tetrachloride, and methylene chloride were detected by the New Jersey Department of Environmental Protection at levels significantly higher than those measured in the air samples. Samples taken from the adjacent Elizabeth River also detected many known carcinogens, including pesticides that had been barred from commerce for years Weinberg, 1980).

Nearly $4 million has been spent by the U.S. Coast Guard to treat contaminated groundwater at the site.   The state of New Jersey alone has spent $5 million on the cleanup of the Chemical Control site.   The O. H. Materials Company, New England Pollution Control, and Rollins Environmental Services, Inc. replaced Coastal Services as contractors in the post-fire cleanup operation.   An inspection of records on the Spill Compensation Fund conducted by the Newark Star-Ledger newspaper pointed to instances of improper and careless handling of waste materials, inconsistent and improper authorization of billings by subcontractors, and inattentive and negligent supervision of the cleanup operation by the New Jersey Department of Environmental Protection (Jaffe, 1982).

MODELING THE TRANSPORT OF TOXICS FROM THE CHEMICAL CONTROL FIRE

The task of computing human exposures to contaminants in the Chemical Control fire plume divides quite naturally into steps.   In the first, we estimate the source term provided by the fire to the air transport model; in the second we model the transport of that source material by the ambient air. We will see that the first step is very difficult, in principle and in practice, so that we will have to be satisfied with rough estimates. But the second is relatively straightforward: established models of plume transportation can be modified to do the calculations.

Releases from a Fire: Computational Problems and Heuristic Assumptions

The Chemical Control site was covered by stacks of drums containing mixtures of unknown composition. Since those wastes were confined in drums, releases to the atmosphere of either the wastes or their combustion products required the rupture, by some mechanism, of the drums that were sealed. From

pictures Of the site taken during the fire, it seems clear that both explosive rupture of individual drums and the rupture of drums in collisions with one another occurred (see figures 12a and 12b). The startling pictures of individual drums propelled tens of meters into the air are clear evidence that, during the fire, substantial kinetic energy was imparted to individual drums. At those kinetic energies, collisions leading to the rupture of individual drums clearly are possible.

Consider, then, the problem of computing the source term contributed by even an "idealized" Chemical Control type fire. That computation requires an estimate of the distribution of kinetic and internal energies among drums, a distribution of the spatial and temporal pattern of releases from drums, and an estimate of the level and composition of combustion products from the associated fire.

That detailed computation will probably never be done. No good inventory of the types, quantities, and locations of materials at the site during the fire exists that might otherwise serve as a guide to a reconstruction of the combustion process. Even if a complete inventory existed, our ability to model the combustion products from even controlled laboratory fires is limited by the complexities of fire chemistry. For example, the current state of the art in simple flame modeling will not sustain a good prediction of the results of small, simple experiments. The experimental results are in fact found to depend, in ways as yet incompletely understood, on the source geometry. That is true even for such mundane materials as wood, which generates a large number of organic combustion products, many of them toxic when burning.

From our description of the Chemical Control fire, it should be clear that any computation of releases based on the combustion process is far beyond the current state of the art of fire modeling. An alternative to modeling the combustion process is to assume a distribution of releases from the fire based on the mass of the source term. The U.S. Environmental Protection Agency reports that approximately 50,000 drums were removed from the site In the post-fire cleanup operations (U.S. EPA, 1982). Estimates of the number of drums at the site during the fire have ranged from between 24,000 to 50,000 (table 23). Since the remains of 50,000 drums were recovered in the post-fire cleanup operation, we will center our analysis of that estimate. At the density of water, if each drum had a capacity of fifty-five gallons, then 50,000 drums of hazardous materials on the site would translate into a mass of 1.04 x 10^7 kilograms. Therefore, if all the material is converted into toxic smoke,[4] the mean source emission rate over a twelve-hour period would be about 280 kilograms per second. Of course the actual mass emission rate will vary over the course of the fire. We therefore assume that the emission rate would be highest in the second three-hour period, and lower in the others. Case 2 of table 24 summarizes the fire parameters constructed on the basis of these assumptions. Because the assumptions are somewhat arbitrary, we introduce two other cases by varying some of the descriptive parameters. Damage calculations will be performed for all three cases.
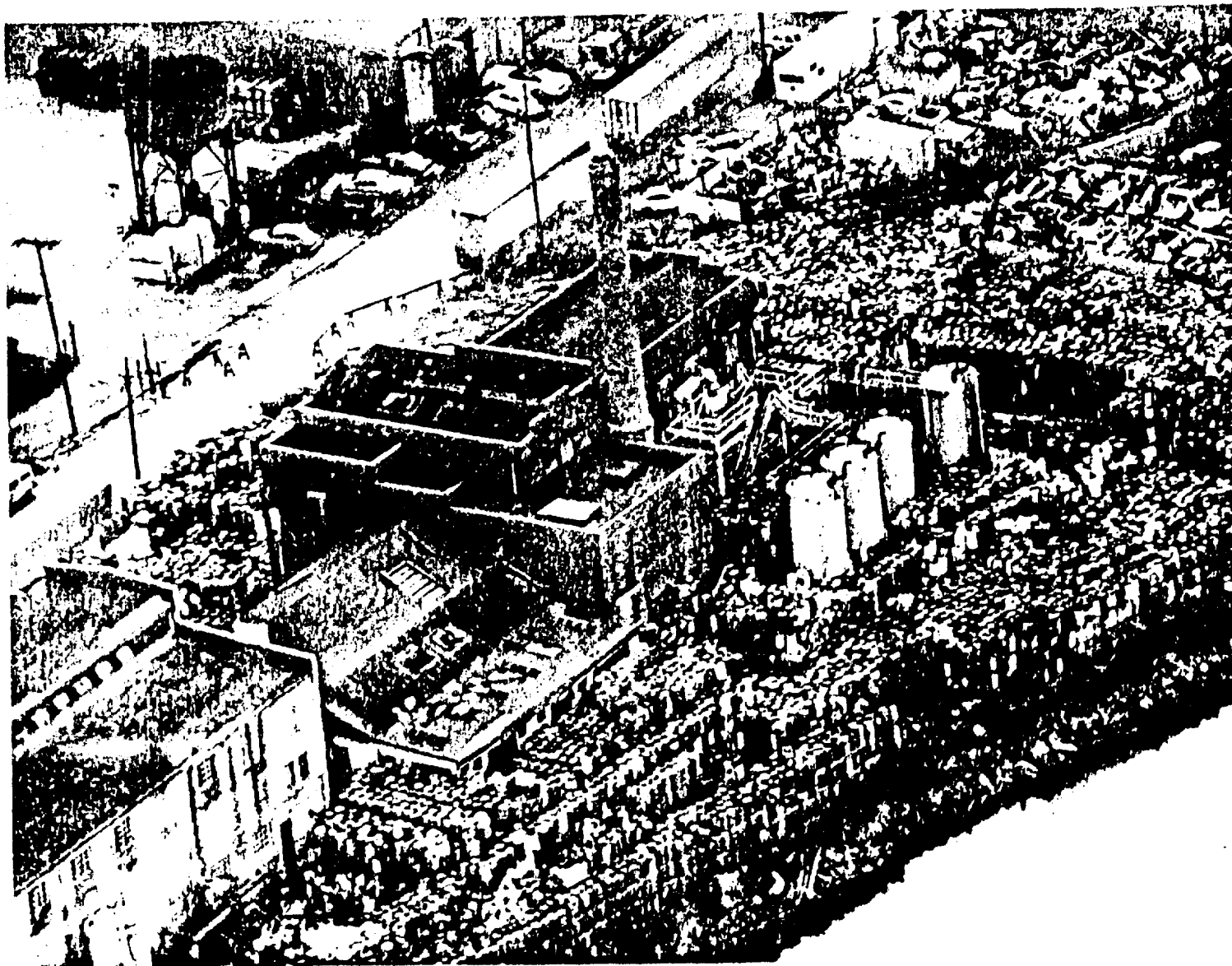
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Figure 12a. The Chemical Control Site Before the Fire

Figure 12b. The Chemical Control Site After the Fire

Table 23. Estimates of Comparison of Number of Drums at the Chemical
Control Facility (Prior to the Cleanup Operation, Removed by the
Cleanup Operation, and Remaining at the Time of the Fire)

Reference	Number of Drums		
	Pre-fire Cleanup*	Removed by Cleanup**	Remaining After Cleanup*
U.S. EPA (1982)	(58-60,000)	8-10,000	50,000
Regenstein (1982)	over 50,000	8-10,000	(40-42,000)
Weinberg (1980)	(58-60,000)	8-10,000	over 50,000
New York Times (1980)	(32-34,000)	8-10,000	over 24,000
Time (1980)	(32-34,000)	8-10,000	over 24,000
New York Times (1979)	45-50,000	8-10,000	(35-42,000)

*Numbers in parentheses show values implied by other data

**Generally agreed that between 8-10,000 drums were removed by pre-fire
cleanup operation.

Calculations of the Transport of Toxics from the Chemical Control Fire

We now turn to the task of translating the source release term assumptions of table 24 into human exposures. Standard models of the transport of air pollutants can be adapted to calculate concentrations based on random meteorological conditions that reflect the uncertainty of the timing of the fire. In principle, the fire could have occurred under any of the wind speed and wind directions drawn from the distributions of those conditions characteristic of the Chemical Control site. Calculations based on a probabilistic distribution of meteorological conditions can therefore be thought of as calculations based on a random start-of-fire time.

The Gaussian plume model of atmospheric transport, described in the following section, is used to calculate concentrations at specific points based on emission rates (see following section), wind speed and direction, and some auxiliary variables, observed at three-hour intervals. The duration of the actual Chemical Control fire was between ten and twelve hours; we will assume that the fire was completely extinguished after twelve hours and that releases in the last three-hour interval were significantly less than in the other three-hour intervals (see table 24).

Ambient concentrations at one kilometer incremental distances from the site are computed for each set of meteorological conditions. Dose concentrations are then averaged over a constructed probability distribution of four sequences of three-hour periods to account for shifts in wind direction. Population exposures to the ambient concentrations and health damages thereof are calculated based on these averaged dose concentrations. Finally, the cost of bearing the risk of health effects is computed. That cost is of course identical with the benefit associated with avoiding an incident of this type (see chapter 8).

A Model of Air Transport

The model we will use is conventional and can be adapted to our computational needs. Figure 13 represents a "didactic" abstraction of the Chemical Control incident. There is a fire in a waste dump located just west of an urbanized area. The problem is to compute population exposures resulting from air transport of the plume generated by the fire during each three-hour period of assumed steady wind direction and speed.

The transport model we use is the standard Gaussian plume model of atmospheric dispersion (Basta and Bower, 1982). We introduce the following variables and notation:

$C(x, y, z; h)$ Pollutant concentration at point x, y, z for a stack height h **(micrograms/meter^3)**

Q Emission rate (grams/sec)

u Wind speed (meters/sec)

Table 24.   Source Release Term Assumptions, Three Cases, Chemical Control
           Fire

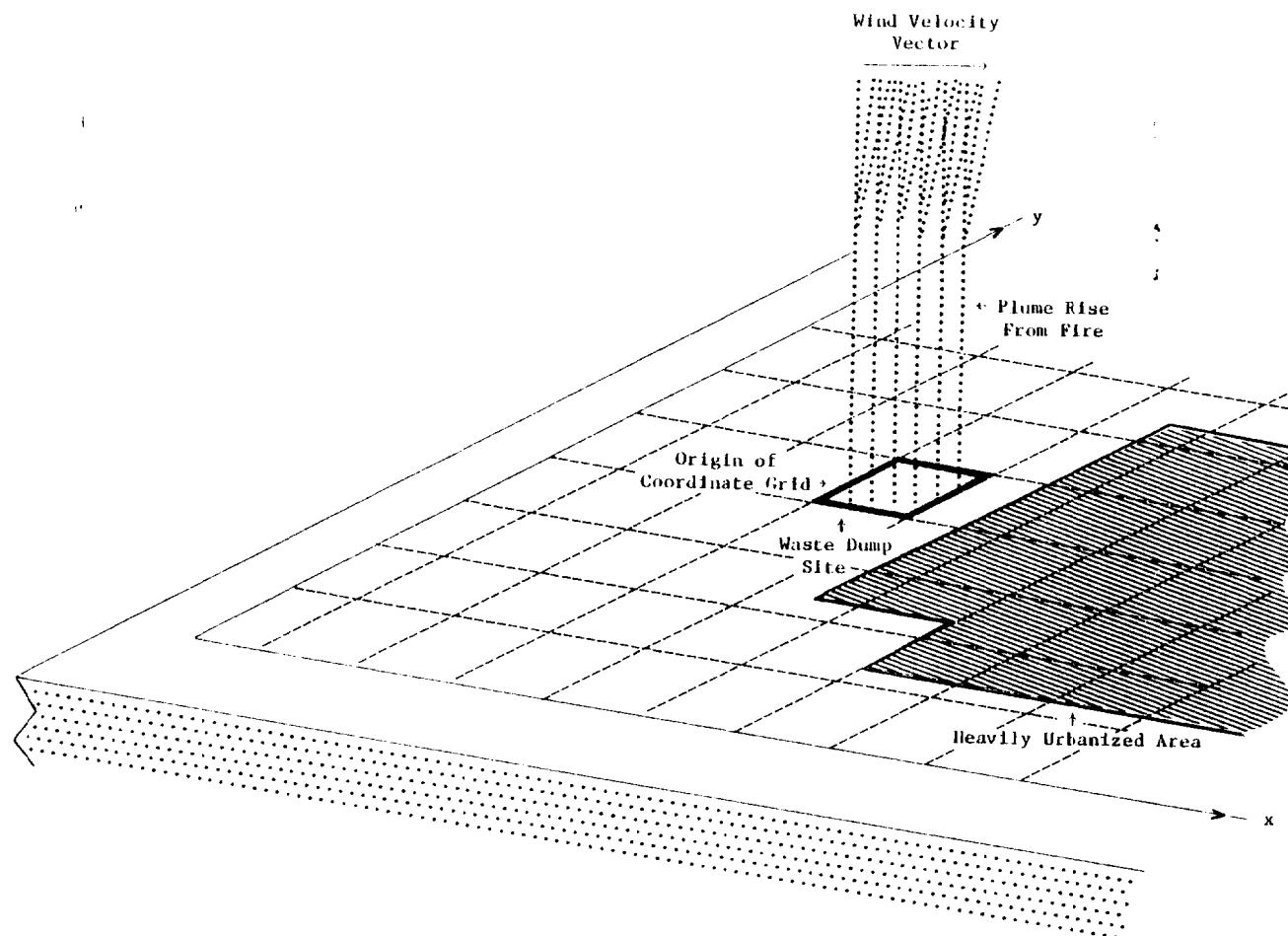| Parameter or Variable	Case 1	Case 2	Case 3
Number of fifty-five gallon drums on site	50,000	50,000	40,000
Fraction of mass volatized in toxic form during fire	50%	100%	100%
Duration of fire, in hours	9	12	12
Fraction of burn in successive three-hour intervals	(0.2, 0.6, 0.2, 0.0)	(0.2, 0.5, 0.2, 0.1)	(0.2, 0.5, 0.2, 0.1)
Mean emission rate, in kilograms per second, for twelve-hour fire	321	240	192

Wind Velocity
Vector

y

Plume Rise
From Fire

Origin of
Coordinate Grid

Waste Dump
Site

Heavily Urbanized Area

x

Figure 13. Topography for the "Didactic Chemical Control Incident" Case Study

σ_y	Horizontal plume diffusion parameter (meters)
σ_z	Vertical plume diffusion parameter (meters)
x	Distance from the source measured along wind direction (meters)
y	Crosswind distance from the source (meters)
z	Vertical distance from the source (meters)
h	Stack height (meters)
H	Effective stack height (meters)
P	Plume rise (meters)

In terms of those variables, the Gaussian plume formula is:

$$C(x, y, z; h) = \frac{10^6 Q}{2\pi\sigma_y\sigma_z} \exp\left(\frac{-1}{2}\left(\frac{y}{\sigma_y}\right)^2\right)$$

$$\left[\exp\left(-\frac{1}{2}\left(\frac{z-h}{\sigma_z}\right)^2\right) + \exp\left(\frac{-1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right)\right]$$

$$(7.1)$$

The relationship between the topography and the coordinates appearing in equation (7.1) may be easier to understand with a glance at figure 14, which orients the coordinate system with respect to the plume.

For computation of human exposures, it is of course ambient concentration at ground level that is relevant. That means taking equation 7.1 for the case z = 0, which gives:

$$C(x, y, 0; h) = \frac{10^6 Q}{\pi\sigma_y\sigma_z u} \exp\left(\frac{-1}{2}\left(\frac{y'}{\sigma_y}\right)^2 \quad \exp \quad \frac{-1}{2}\left(\frac{H}{\sigma_z}\right)^2\right) \quad (7.2)$$

where the effective stack height H is (by definition) the sum of stack height and plume rise:

$$H = h+p$$

It is important to remember the assumptions under which equation (7.1) (and thus equation (7.2)) is valid. These include:

(GP1) Steady-state atmospheric conditions